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The colours of satellite galaxies in the Illustris simulation

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ABSTRACT

Observationally, the fraction of blue satellite galaxies decreases steeply with host halo mass, and their radial distribution around central galaxies is significantly shallower in massive ($M_* \geq 10^{11} M_\odot$) than in Milky Way-like systems. Theoretical models, based primarily on semi-analytical techniques, have had a long-standing problem with reproducing these trends, instead predicting too few blue satellites in general but also estimating a radial distribution that is too shallow, regardless of primary mass. In this Letter, we use the Illustris cosmological simulation to study the properties of satellite galaxies around isolated primaries. For the first time, we find good agreement between theory and observations. We identify the main source of this success relative to earlier work to be a consequence of the large gas contents of satellites at infall, a factor ~ 5 – 10 times larger than in semi-analytical models. Because of their relatively large gas reservoirs, satellites can continue to form stars long after infall, with a typical time-scale for star-formation to be quenched ~ 2 Gyr in groups but more than ~ 5 Gyr for satellites around Milky Way-like primaries. The gas contents we infer are consistent with $z = 0$ observations of H I gas in galaxies, although we find large discrepancies among reported values in the literature. A testable prediction of our model is that the gas-to-stellar mass ratio of satellite progenitors should vary only weakly with cosmic time.

Key words: galaxies: evolution – galaxies: haloes – galaxies: structure.

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1 INTRODUCTION

The observed properties of satellite galaxies can provide insight on a number of processes related to their environments, and provide clues about the intrinsic properties of these objects when they were first accreted by their hosts. Galaxies that orbit within larger gravitational potentials are subject to a variety of physical effects that can significantly decrease their star formation activity, including tidal and ram-pressure stripping and the suppression of a supply of fresh gas. Reddening, mass-loss, and morphological transformations are among the most likely outcomes in response to such environmental effects. Moreover, the strength of these processes will typically decrease at large distance to the host halo centre.

Observationally, it is found that satellite galaxies have a projected number density distribution close to a power law (e.g. Sales & Lambas 2005; van den Bosch et al. 2005; Jiang, Jing & Li 2012; Nierenberg et al. 2012; Tal, Wake & van Dokkum 2012), that is similar to the steep distribution of dark matter expected in their hosts. But, when split by colour, it is expected that blue/star-forming objects should be under-represented in the inner regions, leading to a shallower radial distribution of blue satellites compared to the red population. Observations suggest that this is indeed the case for satellites orbiting groups and clusters with relatively massive primaries. However, for systems with a central galaxy of intermediate to low stellar mass, most of the satellites with stellar masses above $\sim 10^8 M_\odot$ are blue, including those in the inner regions (Prescott et al. 2011; Wetzel, Tinker & Conroy 2012; Guo et al. 2013; Wang et al. 2014).

Significant theoretical effort has been devoted to reproducing these trends with satellite colours. A fair comparison with observations requires a large number of systems to be analysed, motivating

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the use of semi-analytical catalogues and ad hoc tagging techniques preferable over hydrodynamic simulations. However, these models consistently appear to overestimate the fraction of red satellites and fail to reproduce the steep slopes of the blue population around low-mass primaries (Weinmann et al. 2006; Kimm et al. 2009; Guo et al. 2013; Wang et al. 2014). This has traditionally been attributed to an overestimate of environmental effects, possibly related to an improper handling of cold/hot gas evolution in satellites leading to overly rapid quenching (Font et al. 2008; Kang & van den Bosch 2008; Weinmann et al. 2010; Kimm, Yi & Khochfar 2011). However, by suppressing all environmental effects Wang et al. (2014) recently showed that while this would increase the fraction of blue satellites, their radial distribution would still be significantly shallower than observed. The main difficulty seems to be in fuelling star formation for several Gyr after a satellite has been accreted by its primary host.

In what follows, we examine the distribution of satellites by colour using the recently completed hydrodynamical simulation ‘Illustris’. Our results offer a new perspective on the issues at hand by self-consistently following the details of internally- and externally-driven evolution of satellites, explicitly accounting for both their dark matter and baryonic components.

2 NUMERICAL SIMULATIONS

Satellite and primary galaxies are selected from the ‘Illustris’ hydrodynamical simulation¹ (Genel et al. 2014; Torrey et al. 2014; Vogelsberger et al. 2014a,b). This simulation is based on a large cosmic volume (106.5 Mpc on a side) with global properties consistent with a *WMAP*-9 cosmology (Hinshaw et al. 2013) and evolved using the moving-mesh code *AREPO* (Springel 2010). Dark matter, gas and stars are followed from redshift $z = 127$ to $z = 0$. The simulation includes a treatment of the astrophysical processes thought to be most important for the formation and evolution of galaxies, such as gravity, gas cooling/heating, star formation, mass return and metal enrichment from stellar evolution, and feedback from stars and supermassive black holes. The model reproduces a number of key observable properties of the galaxy population at the present-day and at higher redshifts, including stellar mass functions, scaling relations, colour distributions, and the morphological diversity of galaxies.

Individual objects in the simulation are identified using the *SUBFIND* algorithm (Springel et al. 2001; Dolag et al. 2009) and are divided into ‘central’ and ‘satellite’ galaxies according to their rank within their friends-of-friends (FoF) group, so that the ‘central’ object corresponds (in their majority) to the most massive subhalo of the group. In what follows, we consider all *central* galaxies with stellar mass $M_* > 10^{10} M_\odot$ as isolated primaries and study the distribution and colour of their surrounding *satellites* that belong to their FoF groups and that are more massive than $M_* > 10^8 M_\odot$. At the resolution of the simulation (mass per particle $m_p = 6.3 \times 10^6 M_\odot$ and $1.3 \times 10^6 M_\odot$ for dark matter and baryons, gravitational softening $\epsilon \sim 500$ at $z = 0$), all such ‘satellites’ are resolved with ~ 100 or more stellar particles. Stellar/gas mass and $(g - r)$ colours of simulated galaxies are measured within twice the stellar half-mass radius. Virial quantities correspond to the radius where the spherically-averaged inner density is 200 times the critical density of the Universe.

Our simulations track the evolution of satellite galaxies self-consistently, combining internal processes such as star formation and feedback with external effects due to the environment, such as tidal stripping, dynamical friction, ram-pressure, gas compression by shocks, etc. The *AREPO* code is well suited to handle the fluid and gravitational instabilities expected to arise in such complex configurations, with the creation of hot bubbles due to stellar/AGN winds, gaseous tails due to ram pressure, stellar streams and shells. We have used a lower resolution box to confirm that the results do not depend strongly on resolution. Our sample comprises 9529 satellites around 3306 primary galaxies at $z = 0$.

3 RESULTS

The left-hand panel of Fig. 1 shows the projected radial distribution of satellites around primaries in different stellar mass bins, as indicated in each panel (in log-scale). We consider all satellites that are within the 3D virial radius of their hosts (taking all satellites in the FoF group changes only slightly the outer regions). The projected profiles, Σ_{sat} (black solid lines), correspond to the average number of satellites found per primary at a given projected separation r_p (direction of projection chosen randomly) and normalized to the virial radius of the host halo r_{vir} . An interesting outcome is seen by comparing this with the shaded grey area which shows the 25–75 per cent distribution for the dark matter profiles in these haloes (normalized arbitrarily so that they intersect at $r_p/r_{\text{vir}} = 0.5$). We find that satellite galaxies roughly follow the underlying distribution of dark matter in the distance range $0.2 \leq r_p/r_{\text{vir}} < 1$, with a trend to flatten towards the inner regions. Previous works have shown no consensus on this issue, although most of the discrepancies might be explained by different selection criteria and distance range considered (see section 1, Wang et al. 2014).

The left-hand panel of Fig. 1 also shows (dashed magenta lines) observational results based on photometric and spectroscopic SDSS data from Wang et al. (2014). In this work, primaries are identified following isolation criteria for their projected distance and redshift distributions, while satellite profiles result from the photometric SDSS sample after properly accounting for background/foreground objects through a subtraction method. Stellar mass cuts in primaries and satellites are similar to our analysis. The good agreement between the slopes and normalizations of the black solid and dashed magenta lines is encouraging, especially taking into account the different selection criteria used in the two samples. (For the least massive bins, the background subtraction method and the isolation criteria can have a significant impact on the profile slopes obtained; see the appendix in Wang et al.)

We explore satellite profiles split by colour in the right-hand panel of Fig. 1. Here, we adopt a uniform colour cut $(g - r) = 0.5$ independent of satellite mass, but we have explicitly checked that this choice does not qualitatively bias our results. For the most massive primaries ($\log(M_*/M_\odot) > 11$), red satellites dominate the overall population and tend to be distributed more steeply than the blue ones, especially for the four most massive primary bins. However, in lower mass systems, satellites are predominantly blue and exhibit a steeper radial profile than in more massive systems. We quote in each panel the slope found for each population and its uncertainty based on 100 bootstrap resampling of the data. These trends agree well with observations, including the SDSS results of Wang et al. (2014) – shown here by the red/blue dashed lines (see also Guo et al. 2013). Reproducing these behaviours and the abundance of blue satellites around low-mass primaries has been a challenge in theoretical models of galaxy formation based on

¹ <http://www.illustris-project.org>

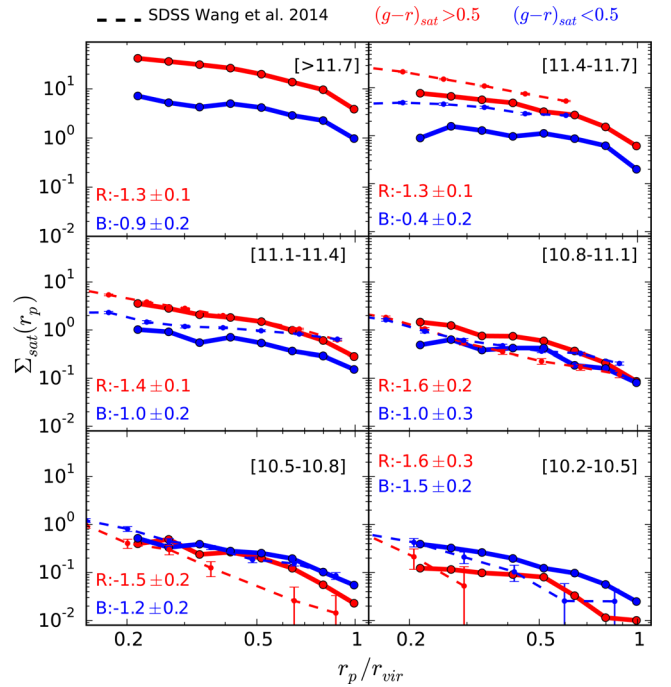
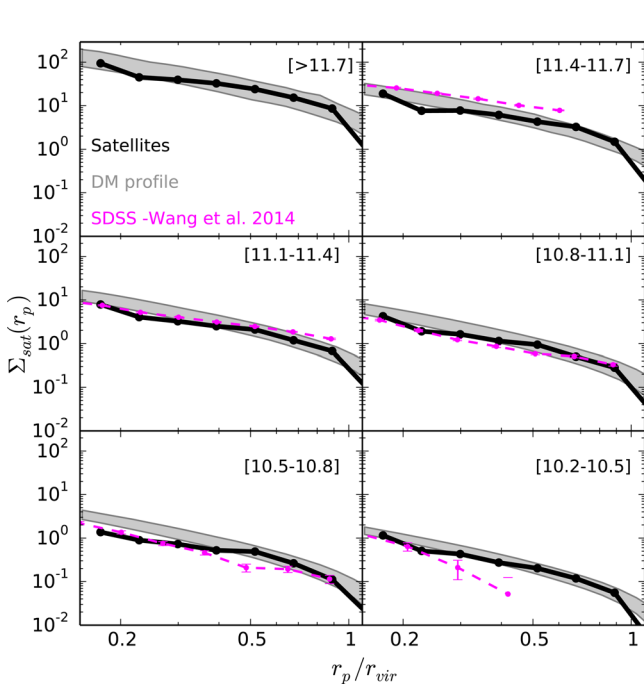


Figure 1. Left: projected number density profile of satellites, Σ_{sat} , in Illustris. Panels correspond to different primary galaxy stellar masses, as indicated (in log-scale). Satellites approximately follow the distribution of dark matter particles in their host haloes, as shown by the grey shaded area corresponding to the 25–75 per cent percentiles of the sample (arbitrarily re-normalized such that satellites and DM profiles intersect at $r_p/r_{\text{vir}} = 0.5$). Dashed magenta lines show results from the SDSS analysis presented in Wang et al. (2014). Right: same as left-hand panel, but satellites are divided into red and blue populations. Fits to the profiles’ slopes are quoted in each panel. Our simulations (solid) successfully reproduce two key aspects of the SDSS results (dashed): (i) a dominant red(blue) population for high(low)-mass primaries and (ii) a steep profile of the blue satellites orbiting low-mass primaries (bottom row).

semi-analytical methods, but they seem to arise naturally in our simulations.

Variations in satellite infall times for a wide range of primary masses could explain their different colour distributions. However, we find that t_{inf} is roughly independent of primary mass, as shown by the median relations (black dashed curves) in Fig. 2. We define t_{inf} as the last time a satellite was a central galaxy of its own FoF group, and explicitly checked that using a different definition (e.g. the time when the satellite joins the FoF group to which it belongs at $z = 0$) yields similar results. When we split satellites by their own colours we find large differences. In the most massive systems, regardless of the projected distance of the satellite, blue objects have typically fallen in only recently, fewer than ~ 2 Gyr ago. Instead, for primaries comparable to the Milky Way, the median infall time of blue satellites in the inner regions is ~ 5 Gyr ago, with individual cases scattering down to > 7 Gyr.

Interestingly, red satellites cease forming stars on very different time-scales according to their orbits: they show slow gas consumption in wide orbits to rapid single pericentre episodes for very radial ones. In general, surviving satellites maintain a similar stellar mass to that at infall, although a few per cent (2–10 per cent, depending on primary mass) more than double their stellar content during their lives as satellites (see also Pillepich et al. 2014). Appreciable stellar stripping occurs only for red satellites, but the impact is small; fewer than 3 per cent have lost at least half their initial stellar mass. These results are in reasonably good agreement with the standard treatment of star formation in satellite galaxies employed in semi-analytical models (SAMs).

We find that a key factor in achieving a prolonged star formation for satellites in Fig. 2 (and therefore, producing the good match between observed satellite colours/distribution) is the large gas

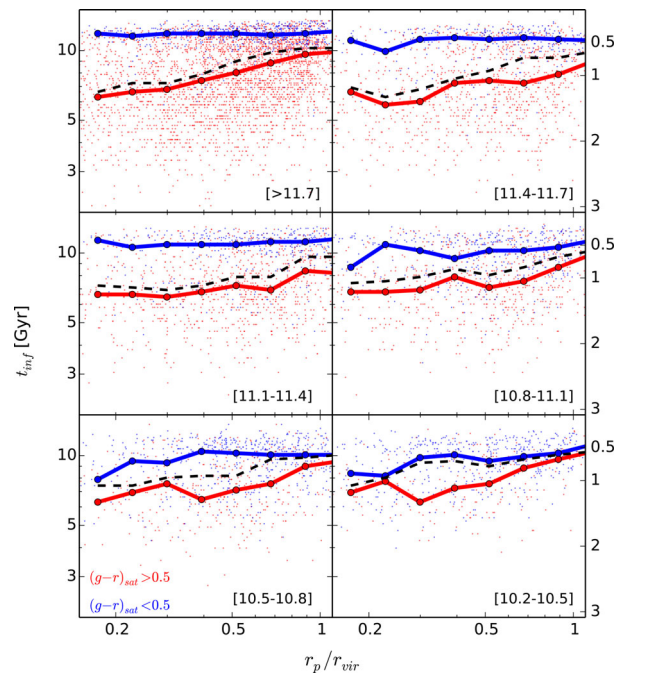


Figure 2. Infall times t_{inf} for satellites as a function of present-day projected distance (right y-axes display corresponding redshifts). Points indicate individual satellites and red/blue corresponds to their $(g-r)$ colours at $z = 0$. The median trend considering all satellites is shown by the black dashed lines and is roughly independent of the primary stellar mass (different panels). However, when split by colour (solid curves), satellites that remain blue today can have significantly earlier infall times in low-mass primaries (bottom two panels) than in more massive hosts.

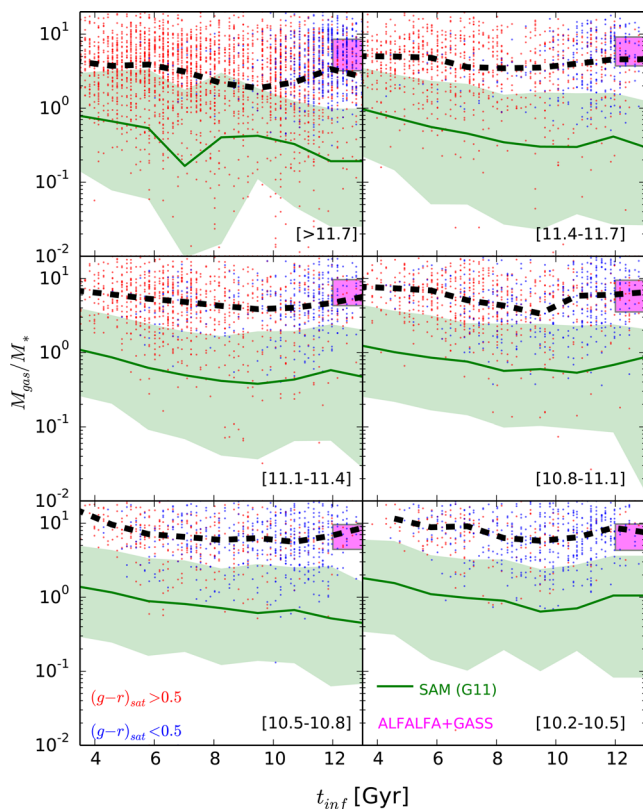


Figure 3. Satellite gas-to-stellar mass ratios at infall, M_{gas}/M_* , as a function of infall time. As earlier, the panels correspond to different primary stellar masses, red/blue denotes $(g-r)$ colours of satellites at $z=0$ and the median trend is shown by the black dashed curves. (The vertical stripes in the points’ distribution reflect the finite number of output times.) In Illustris, satellites infall with a large gas content ($M_{\text{gas}}/M_* \sim 2-8$) that allows them to form stars for several Gyr. The gas contents in our model are, at present epoch, in good agreement with observational estimates from the ALFALFA and GASS surveys (magenta rectangles; see the text for more details). The green shaded region indicates gas-to-stellar mass ratios adopted in SAMs (in this case taken from Guo et al. 2011), which are substantially lower than in our simulations. This appears to be a key factor to explaining the overproduction of red satellites in SAMs.

contents of satellites at infall. Fig. 3 shows, in bins of primary stellar mass, the infall gas-to-stellar mass ratios M_{gas}/M_* of satellites as a function of their infall times. We consider all gas particles within twice the stellar half-mass radius and we have checked that it is dominated (in more than 90 per cent) by the cold ($T < 2 \times 10^4$ K) plus star-forming components. The median in our simulations suggests that, at infall, satellites have $\sim 2-5$ times more gas than stars. We also find a weak trend of M_{gas}/M_* with the primary stellar mass (different panels), that is a consequence of the most massive systems having more massive satellites, which are, on average, less gas-rich than the lower mass dwarfs that dominate the satellite population of intermediate- and low-mass primaries (see fig. 3 in Vogelsberger et al. 2014a for the mass-dependent nature of gas contents in our simulations and observations).

To relate our finding with previous results in the literature, we compare our simulated gas contents with those from the publicly available SAM of Guo et al. (2011), which has itself (or its predecessors) been extensively used in the study of satellite galaxy properties. We select primaries and satellites from the Millennium-II volume (Boylan-Kolchin et al. 2009) with the exact same selec-

tion criteria as employed in analysing our simulations. The median (green solid line) and 10–90 percent percentiles (shaded area) of the distribution of cold gas-to-stellar mass ratios in the SAM are shown in Fig. 3. The difference with the simulated data is striking, in the sense that the galaxies are approximately a factor 10 times less gas-rich in the semi-analytical catalogue than in Illustris. We have checked that this is independent of satellite stellar mass and is also present for *central* galaxies in the model. On this basis, we argue that the relatively low gas content of satellites at infall in the SAMs is largely responsible for their failure to reproduce the colour and distribution of satellite galaxies.

Unbiased observational estimates of gas contents are challenging, especially for low-mass objects. Gas fractions reported in the literature show large variations depending on the observational strategy. Optically selected samples find systematically lower gas fractions than H I-selected samples like ALFALFA (see Papastergis et al. 2012). Ideally, the best constraints should come from mass-complete, optically selected samples like GASS (Catinella et al. 2010). However, presently these surveys are restricted to only massive galaxies ($M_* > 10^{10} M_\odot$). Because low-mass central galaxies are mostly star forming, we assume that satellites before infall follow ALFALFA reported gas fractions from Huang et al. (2012) if $M_* < 10^{10} M_\odot$ but that of GASS if they are more massive. The magenta rectangles in Fig. 3 indicate the gas-to-stellar mass ratios obtained by assigning to each simulated satellite with a recent infall time ($t_{\text{inf}} > 12$ Gyr) the gas content according to this ALFALFA+GASS combination, a 0.3 dex dispersion around the mean, and assuming a mass-independent molecular fraction of 0.3 (Saintonge et al. 2011). The simulated values are in good agreement with what would be expected from such observations at $z=0$.

Lastly, since the parameters in the model used in Illustris were not calibrated to reproduce gas quantities, the weak dependence of the (total) gas-to-stellar ratio with infall redshift is actually a prediction of our model. Interestingly, an independent analysis of the stellar mass–metallicity relations at several redshifts (Zahid et al. 2014) also seems to indicate such a weak evolution.

4 CONCLUSION

We use the Illustris cosmological simulation to study the distribution of satellite galaxies around isolated primaries. The large volume of our simulated box allows us to statistically characterize ~ 9500 satellite galaxies with $M_* > 10^8 M_\odot$ orbiting primaries with masses comparable to the Milky Way and above. This is the first time such a study has been performed using a hydrodynamical simulation.

We find good agreement between our results and observations from the SDSS wide field survey. In our simulations, (i) satellites roughly trace the distribution of dark matter in their hosts, and (ii) in high-mass systems, red satellites dominate and are distributed more steeply than the blue population, whereas for lower mass primaries, satellites are mostly blue and they also follow a steep number density profile. This good agreement with the observations contrasts with earlier theoretical modelling, mostly based on semi-analytical techniques, which were unable to reproduce the satellite colour–primary mass dependent behaviour seen in the observations. Based on the SAM output of Guo et al. (2011), we suggest that gas contents that are too low for satellites at infall (and not the modelling of environmental effects) is the most likely cause of the challenges faced by such models in reproducing observations.

Our simulations provide a tool for understanding the time-scales for the quenching of star formation in different environments. At

infall, simulated satellites carry significant amounts of gas, with quartiles $M_{\text{gas}}/M_* = 2\text{--}8$, that can fuel star formation for long periods of time. Moreover, we find a very weak evolution of gas-to-stellar mass ratios with redshift, a testable prediction of the model that can be explored once observational estimates of total gas mass become available for galaxies at higher redshifts.

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